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SCIENCE

COMET AND CLOSE-APPROACH ASTEROID MISSION STUDY

FINAL REPORT

VOL. 2

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Prepared for

Jet Propulsion Laboratory
Pasadena, California

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Contract JPL 950870

Prepared by

PHILCO CORPORATION
A Subsidiary of Ford Motor Company
WDL Division
Palo Alto, California

Prepared for

Jet Propulsion Laboratory
Pasadena, California

FOREWORD

This document is the final report of work performed on Science by the WDL Division of the Philco Corporation during the Comet and Close-Approach Asteroid Mission Study for the Jet Propulsion Laboratory under Contract JPL 950870. The report covers work performed during the period 2 July 1964 to 2 January 1965.

ACKNOWLEDGMENT

This volume was prepared by Albert Giddis with a contribution to the Brightness Model section by **Professor L. E. Cunningham of the University of California Astronomy Department.**

SUMMARY

The report analyzes what is known about the geometry, brightness and composition of comets to the extent necessary for conducting a mission analysis and for designing conceptual spacecraft. Such comet "models" have been developed to specify requirements of scientific instruments for performing comet measurements, to assess the applicability of existing instrumentation, and to determine the influence of the comet environment upon subsystem design and mission capability. Astrophysical and exobiological scientific objectives have been identified and representative comet payloads established to determine the distribution of matter and magnetic field during a fly-through, to observe the nucleus and its surrounding region, and to determine cometary chemical composition.

Scientific measurements performed from on-board a spacecraft during its intercept with a comet fulfill two roles in determining the composition of comets. The first function is to complement measurements performed from earth astronomical observatories by direct sampling of the particle, field and molecular composition of a comet, by close-range observation of its physical features, and by detecting predicted but unobserved spectral emissions. The second function is to supplement measurements performed on the earth by confirming spectral lines previously recorded, especially those that are ambiguously identified. On-board measurements can better serve their complementary and supplementary functions if they are correlated with simultaneous photometric and spectroscopic observations from Earth.

The compatibility of particle-and-field experiments for comet intercepts with basic interplanetary measurements is unique to this

type of encounter mission.

The scientific feasibility of comet missions with an Atlas-Centaur launch vehicle during 1967-1975 has been established.

A mission to the close-approach asteroid Eros is outlined to establish growth potential for the comet probe.

The scientific feasibility of a comet mission to Pons-Winnecke with an Atlas-Agena/Mariner-C during late 1969 and early 1970 has been established.

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SECTION 1
SCIENTIFIC OBJECTIVES

1.1 ASTROPHYSICS

Astrophysicists believe that a definitive insight into the origin and formation of comets and planets will be gained by exploring comets and asteroids with space probes [Whipple, 1963; Swings, 1962a; Newburn, 1961]. Much data must be collected for many years in order to refine or to reject extant theories about the evolution of the solar system [Lyttleton, 1953], about the physics of cometary and asteroidal bodies themselves [Wurm, 1963; Biermann and Lust, 1963; Robey, 1962], and about the dynamics of the interplanetary medium [Brandt, 1961; Brandt, 1962].

There appears to be agreement within the scientific community that, as with the moon and planets, the true nature of comets can be revealed only by a direct probing of the coma and tail and by observations and eventual sampling of the nucleus by a space probe. In the meantime, photometric and spectroscopic identification of cometary materials in the laboratory [Benton, 1964] and from ground observations [Swings and Haser, 1956] will be continued.

Plans exist for ejecting artificial gaseous comets from rockets at high altitudes, and great interest has been shown in orbiting an artificial cometary nucleus around the Earth [Donn, 1961]. Observations of natural comets from orbiting observatories have been considered.

Scientific measurements performed from on-board a spacecraft during its intercept with a comet fulfill two roles in determining the composition of comets. The first function is to complement measurements performed from earth astronomical observatories by direct sampling of the particle, field and molecular composition of a comet, by close-range observation of its physical features, and by detecting predicted but unobserved spectral emissions. The second function is to supplement measurements performed on the earth by confirming spectral lines previously recorded, especially those that are ambiguously identified. On-board measurements can better serve their complementary and supplementary functions if they are correlated with simultaneous photometric and spectroscopic observations from Earth.

1.1.1 Origin of Comets and Asteroids

Either comets were formed in the solar system, or they were formed in interstellar space and through some process were captured by the sun's gravitational field. The physical evidence about comets is not inconsistent with their possible origin in interstellar space, but the dynamics of their possible capture and subsequent motion are debatable. The recent discovery by Greenstein and Stawikowski [1964] that Carbon 13 occurs in comet Ikeya in almost the same proportion to C_{12} as it occurs on earth suggests that comets were formed in the solar system. Oort [1963] has suggested that comets were formed in the same region as the planets but were subsequently expelled from the solar system by planetary perturbations into a large "cloud" surrounding the solar system. Stellar perturbations presumably force some of these bodies back into the solar system to smaller perihelion distances until they come under the influence of Jupiter.

It has been conjectured that the asteroids are the remains of the collision of two planets in the region now occupied by the asteroid belt. Some of the smaller asteroids may be the fragments of subsequent collisions among these planetoidal particles.

1.1.3 ESRO Study Group

The European Space Research Organization (ESRO) Cometary Feasibility Study Group has under consideration the study of intercept missions to periodic comets [Biermann, 1964]. A preliminary list of comets for the period 1970-1974 has been established; a document will be issued soon on the physical characteristics of comets Tempel (2), Pons-Winnecke, Brooks (2), Faye, Encke, Honda-Mrkos-Padjusakova, Tuttle-Giacobini-Kresak, Brorsen, Wolf, Tuttle and Halley; and a detailed study of space cometary experiments is being conducted [Swings, 1964]. However, since decisions have not been made officially by the appropriate bodies of ESRO, no information has been authorized for release [Di Benedetto, 1964].

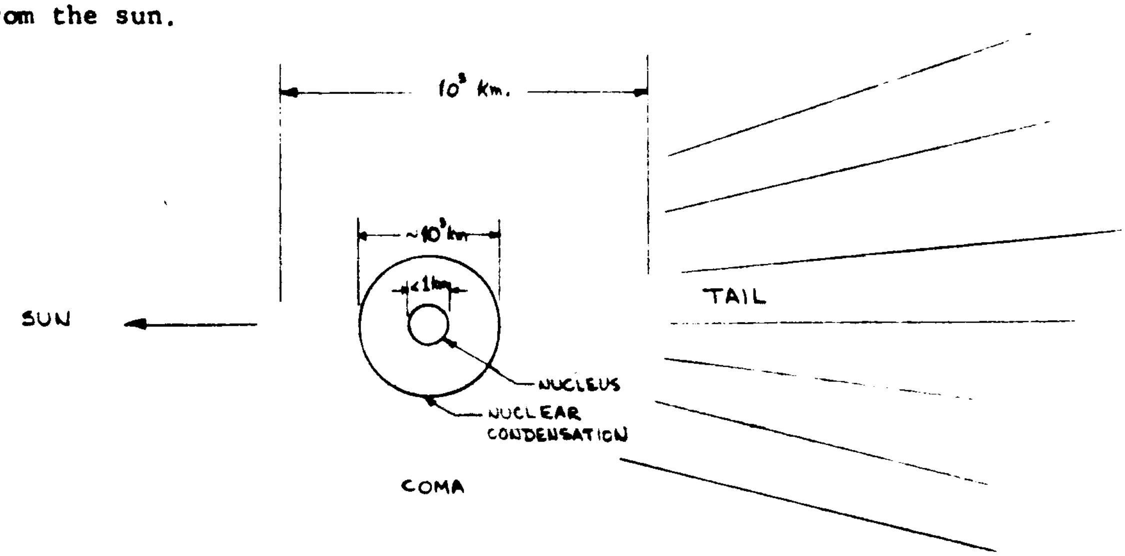
1.2 EXOBIOLOGY

High interest exists in the detection of life throughout the solar system. The possibility of exploring comets to determine the presence of organic compounds fundamental to life has been suggested. Spectroscopic observations of comets indicate unequivocally the presence of CN, C_2, C_3, and CH in the comet's atmosphere (coma). The icy core (nucleus) is presumably composed of the frozen gas molecules CH_4, CO, CO_2, and others.

SECTION 2
COMET MODELS

2.1 GEOMETRY AND COMPOSITION

The geometry of periodic comets selected for first-generation comet missions can be represented by a star-like spherical nucleus of 1 km diameter or less, surrounded by a bright region referred to as the nuclear condensation of perhaps 10^3 km apparent diameter, imbedded in a spherical coma of 10^5 km apparent diameter near perihelion (intercept) between 1 and 2 A.U. The position of the nucleus is generally off-center along the sun-comet line. A faint, short tail extends along this line away from the sun.



The visible size of the coma, as seen from the comet probe, may be larger than as seen from the Earth because, in space, no atmospheric background "noise" exists to mask the faint outer limits of the cometary atmosphere. It has been suggested, for example, that an apparent size of 0.5 deg. measured from the earth may appear to be 3 deg. from the probe at an equal comet-observer distance outside the Earth's atmosphere (this means the same optics also).

The atoms, molecules, and solid particles in the coma and tail originate in the nucleus. The composition of the nucleus is generally accepted to consist of icy compounds (such as water, ammonia, methane, carbon, etc.) partly in the form of solid hydrates with an admixture of meteoritic dust (e.g., metals and silicates) [Wurm, 1963; Lyttleton, 1953; Whipple 1963]. The observed gases in the coma and tail are atoms and di- or triatomic radicals or molecules resulting from sublimation, photodissociation, ionization, and chemical reactions.

Most comae and many tails reveal a solar continuum that is due to the scattering of solar radiation by solid particles [Swings, 1963]. In addition, gases in the coma emit fluorescence spectra as a result of excitation by solar electromagnetic radiation, while gases in the tail show spectra as a result of ionization by solar corpuscular radiation.

The few available data on the composition and physical characteristics of selected periodic comets Tempel (2), Pons-Winnecke, Kopff and Brooks (2) are summarized in Table 2-1 [Cunningham, 1964; Dossin, 1964; Roberts, 1964; Vsekhsvyatskii, 1963]. Their orbital characteristics are discussed in Volume 3.

2.2 BRIGHTNESS MODEL

2.2.1 Distant-Passage Model

The brightness of a comet is usually represented by an empirically justified relation of the form

$$J = \frac{J_o}{\Delta^2 r^n} , \qquad (2\text{-}1)$$

Table 2-1. Data on Selected Periodic Comets

COMET	NUCLEUS	COMA	TAIL	OBSERVED SPECTRUM	ABSOLUTE MAGNITUDE
Tempel (2) (1873 II)	Stellar at > 2 A.U. Central condensation near perihelion	Diffuse coma of nearly 10^5 km diameter	Some tail near perihelion	CN	13.0
Pons-Winnecke (1819 III)	Stellar Diameter 0.4 - 1 km		Short tail	CN, C_2; continuum	12.5 Total Comet 16.4 nuclear condensation
Kopff (1906 IV)		About 10^5 km diameter at perihelion	No significant tail	CN, C_2, C_3, CH; faint continuum	13.8 16.1 - 17.2 nuclear condensation
Brooks (2)	Stellar at > 2.5 A.U. Diameter 2.4 km max	Small, faint, strongly condensed coma	Faint, short tail	CN, C_2, CO^+; continuum	14.4 Total comet 16.1 - 16.6 nuclear condensation

where Δ is the earth-comet distance, r is the sun-comet distance, and n characterizes the degree of central condensation of the comet under observation. Phase with respect to the observer is neglected and comet activity is assumed not to vary widely in time. Values of n range from 2 to 6 generally, with an average of 4, Expressed in stellar magnitudes, the relation becomes

$$m = m_o + 5 \log \Delta + 2.5 n \log r, \tag{2-2}$$

where m_o is an absolute magnitude. Theoretically, it represents the brightness that a comet appears to exhibit at unit distance from the sun and from the earth ($\Delta = r = 1$ A.U.). However, the light from a comet results from sunlight reflected and scattered by the nucleus and dust particles, and from light re-emitted by molecules excited to fluorescence by solar radiation. These different contributions vary with heliocentric distance and the particular apparition, and thus cannot be represented strictly by a magnitude law as the one expressed in Equation (2-2). Nevertheless, the time-honored formula is useful.

2.2.3 Close-Approach Model

The most reliable estimate of brightness distribution has been provided by Professor L. Cunningham of the University of California. Cunningham [1964] has suggested a symmetrical model based upon observations. The symmetry of the illumination contours are attributed to the age of the comet which is a measure of cometary activity, the periodic comets being very old and having a corresponding low activity. Cunningham has indicated that in the region of maximum brightness, the brightness distribution of both the coma and the nuclear condensation of faint, periodic comets near perihelion can be described by exponential functions of angle away from the center of the nucleus. That is,

$$B = B_o e^{-kL^2} \qquad (2\text{-}3)$$

where

B = brightness measured in stellar magnitudes per (minutes of arc)^2

B_o = brightness at the center

L = angular distance measured in minutes of arc away from the center by an observer at 1.0 A.U.

This brightness pattern applies to the coma and the nuclear condensation in which the coefficients k and B_o for Pons-Winnecke are as follows:

Region	k	B_o
Coma	8	$4.0^M/(\text{min.})^2$
Nuclear Condensation	2000	$6.0^M/(\text{min.})^2$

The above model can be converted to stellar magnitudes M at 1 A.U.:

$$M = M_o + 2.5\ kL^2 \log e \qquad (2\text{-}4)$$

where M_o is the absolute magnitude.

2.3 SPECTRAL EMISSION

A tabulation of charactertistic cometary spectra is shown in Table 2-2 [Swings and Haser, 1956; Wurm, 1963; Benton, 1964; Swings, 1962a].

TABLE 2-2. Sampling of Comet Emissions

MOLECULES	WAVELENGTH RANGE (Å)	WAVELENGTHS OF MAXIMUM INTENSITY (Å)	COMET REGION MAXIMUM INTENSITY	HELIOCENTRIC DISTANCE (A.U.)	REMARKS
CN	7900, 8100 (red system)	7906	Near nucleus	< 3	Provisional identification
	3572 - 3882 (ultraviolet)	3584 3882	Near nucleus (extends well into coma)		Determines photo image nearly circular isophotes
C_2	4676 - 6186 (blue-green to yellow)	4713,5165 5634,6118 (Swan bands)	Near nucleus (extends somewhat into head)	≤ 1.8	Determines visual image
C_3	3950 - 4140	4050 group	Near nucleus	≤ 1.7 - 2 A.U.	Steeper gradient than CN
CH	3881 - 3922 4281 - 4348	3903 4313		< 1.5	
OH	3079 - 3159	3096		< 1.5	High abundance
NH	3350 - 3372	3358	Same as C_2	< 1.5	
NH_2	6000 - 6600	6299	(Extends into mid-coma)	< 3	Steeper gradient than CN
O_I	6300,6360 5577				Hard to identify; confused by NH_2 emission
CH^+	3954 - 3973 4231 - 4255	4238	Near nucleus: (small elongation into tail)	< 2	Partly blended with other bands
OH^+	3565, 3616	3565	Head	< 1.5	Ambiguous
	3594, 3616		(Small elongation into tail)		
CO^+	3416 - 5048	(Baldet-Johnson band)	Tail	< 1.5	Most intense tail ion
CO_2^+	3370, 3388, 3509, 3545, 3674, 3695, 3839	3509, 3674	Moderately into tail	< 2	
N_2^+	3545, 3580, 3914, 4231, 4279	3914	Tail	< 1.5	Weaker than CO^+

For the neutral and ionized molecules listed, the table indicates the wavelength range within which emission lines have been detected, the wavelength of maximum intensity, and the comet region within which the maximum intensity is observed, and the maximum heliocentric distance at which the emission spectra can be observed.

Since the heliocentric distances at intercept are less than 1.6 A.U. except for Brooks (2), the molecular emissions listed in Table 2-2 may all be observable with an on-board spectroscope, particularly when it is pointed toward the region of maximum intensity observed previously from Earth. In addition to confirming the presence of positively identified molecules (e.g., CN, C_2, CO^+), it is of high interest to detect emission from ambiguously identified molecules (e.g., O_I, OH^+), from predicted but as yet unobserved ions and stable molecules (e.g., NH^+, H_2, N_2) in the far-ultraviolet region and radicals (e.g., CH_2, CH_3) in the near-infrared region.

Although similarities exist in the spectral emission and hence the molecular composition of periodic comets, as indicated by the observed spectrum in Table 2-1, variations occur among comets that are generally unpredictable. However, it is evident that all those observed spectroscopically contain carbon molecules; i.e., CN C_2, C_3, CH and CO^+.

2.4 PARTICLE DISTRIBUTION

2.4.1 Molecules and Ions

From photometric and spectroscopic observations of such phenomena, the densities of various gases and dust have been estimated in several comets [Swings, 1962c; Sadler, 1962]. The values shown in Table 2-3 have been used as a guide during the study until data become available for the selected comets under study. As shown, the gas densities decrease with increasing distance from the nucleus, and their absolute and relative abundances differ from one comet to another. Although not shown, these parameters also vary with heliocentric distances.

Table 2-3 Representative Comet Densities

COMET	GAS DENSITY		DISTANCE FROM NUCLEUS	DUST DENSITY	
				PARTICLE	REGION
Encke (gas head)	CO^+	1 - 100/cc	10^4 km		
	CN, C_2	3/cc 1/cc 0.5/cc	4×10^4 km 7×10^4 km 9×10^4 km	10^{-9}/cc	Coma
Brooks (2) (gas head)	CN, C_2	10^4-10^6/cc 1 - 10/cc	near nucleus 10^5 km		

2.4.2 Dust

No probable distribution of dust has been generated which can be considered useful for estimating the expected change in dust density and velocity as the spacecraft flies through these comets. A gaseous comet like Encke may have an average particle density of 10^{-9}/cc in its coma.

2.4.3 Electron

Since the coma is considered electrically neutral, the number of electrons should equal the number of ions. In the coma of some comets, only neutral molecules have been detected spectroscopically. An upper limit to the number of electrons can be obtained by assuming that the number of ions is an order less than the number of the weakest neutral molecule detected, e.g., C_2 or C_3. For 10^{31} molecules, this means 10^{30} electrons. For an equivalent uniform comet diameter of 10^5 km, the maximum average electron density is about 1/cc, a value commensurate with the electron density of the interplanetary medium between 1 and 2 A.U. The distribution of electrons through the coma is unknown.

2.4.4 Hydrogen

The proton density in cometary comae is unknown, but not high enough to produce hydrogen in quantities sufficient to generate detectable hydrogen lines. However, 21 - cm emission has been reported.

2.5 RADIO EMISSION

The only reported observations of cometary radio emission have been made on Arend-Roland during its perihelion passage in April 1957. The few data are tabulated below in Table 2-4.

Radio emission at 27.6 Mc [Kraus, 1956] is produced by the interaction of the cometary plasma with solar corpuscular streams. The emission mechanism most likely responsible is the deceleration of cometary ions in a solar corpuscular stream which produces plasma oscillations, usually in the tail region. Dobrovol'skii [1961] has shown that other mechanisms are ineffective in comets; e.g., synchrotron and Cerenkov emission, and interaction of cometary dust with solar protons [Erickson, 1957].

Emission at 1420 Mc [Müller, Priester, and Fischer; 1958], presumably

Table 2-4. Observed Cometary Radio Emission from Earth

FREQUENCY (Mc)	FLUX DENSITY ($w/m^2/cps$)	SOURCE	REFERENCE
1420	(Not given)	Atomic hydrogen (?); Unstable emission	Müller et al [1958]
600	5.6×10^{-23}	CH molecule in head; Stable emission	Coutrez et al [1958]
27.6	5×10^{-22}	Plasma oscillation in tail at more than 10^4 km from nucleus	Kraus [1956]

from atomic hydrogen in the cometary atmosphere, was unstable and cannot be regarded as firm.

Unequivocal radio emission at 600 Mc [Coutrez, Hunaerts, and Koeckelenbergh; 1959] is produced by transitions between fine-structure components due to the so-called Λ-type doubling of rotational levels in the fundamental electronic state of the CH molecule. The number of molecules which might explain the observed flux density at the earth of 5.6×10^{-23} watts/m^2/cps is about 10^{30}- 10^{31}, a value compatible with the estimated population of cometary atmospheres. At 1.5 million km away from the comet, the flux density should be about 5.6×10^{-17} watts/m^2/cps. With a 4-db spacecraft receiver at 600 Mc and for a desired signal-to-noise ratio of 10, the antenna gain required above isotropic is 13.2 (12db). A 60-degree corner reflector or a 2.5-foot long Yagi will yield the necessary effective aperture. However, whether radio emission is detectable in the vicinity of the selected periodic comets is debatable.

2.6 MAGNETIC FIELD DISTRIBUTION

Robey [1962] suggests that the magnetic field distribution in the coma is of the form,

$$B = B_o \left(\frac{d_o}{d} \right)^n , \quad n \leq 1, \qquad (2\text{-}5)$$

for a spherical nucleus of radius d_o surrounded by a concentric spherical coma of radius d, where B_o is the reference magnetic flux density at the surface of the nucleus. The exponent n varies approximately linearly with heliocentric distance from 0.54 to 1.46 A.U. for Encke. Not enough data exists on the selected periodic comets to develop comparable values of n. Therefore, the results for Encke have been used as a model.

Robey has computed that, for Encke with a radius of 1 km, the average flux density at the surface of the nucleus decreases logarithmically with decreasing heliocentric distance, i.e., from 0.2 gauss at 1.5 A.U., to 0.0183 gauss at 1.0 A.U., to 0.006 gauss at 0.5 A.U. The flux at the outer boundary of the coma varies inversely with heliocentric distance; at 1 A.U., it has been calculated to be 48.3×10^{-15} gauss.

SECTION 3

COMET EXPERIMENTS

3.1 PARTICLE AND FIELD MEASUREMENTS

The scientific objectives outlined in Section 1 lead to the identification of scientific experiments in three categories: (a) particle-and-field measurements in the coma, (b) observations of the nucleus, and (c) physicochemical measurements of cometary matter.

A set of eight particle-and-field experiments and a propagation experiment is listed in Table 3-1A along with the physical and performance characteristics of instruments selected to perform the measurements. The instruments are the following:

a. Triaxial helium magnetometer
[Smith, 1964; JPL, 1963 c]

b. Piezoelectric-microphone dust detector
[JPL, 1964; JPL, 1963 c; JPL, 1962 a; NASA, 1963]

c. Electrostatic-analyzer plasma probe
[JPL, 1964; JPL, 1963 a, c; JPL, 1962 a, b]

d. Ion-mass spectrometer
[NASA, 1963]

e. Planar-trap electron detector
[JPL, 1962]

f. Integrating ionization chamber
[JPL, 1963 c; JPL, 1962 a]

g. Trapped-radiation Geiger-Mueller counter
[JPL, 1963 c; JPL, 1962 a]

h. Bistatic-radar receiver
[JPL, 1964]

Among these instruments, the performance of the following depend upon the probe's velocity relative to the comet: dust detector, electron trap, and ion mass spectrometer.

3.1.1 Dust Detector

For a relative velocity, v_h, the minimum particle mass, m_p, detectable with a detector of sensitivity, M, is

$$m_p = M/v_h \tag{2-6}$$

For velocities of 8 to 16 km/sec derived from the trajectory analysis and a sensitivity of 10^{-5} dyne-sec. for the piezoelectric-microphone instrument, m_p ranges from 1.25×10^{-11} to 6.25×10^{-12} gm. The average impact rate for a detector area, A, and an average dust-particle density, ρ, in the coma of a gaseous head comet is

$$i_p = v_h A\rho \tag{2-7}$$

The impact rates range from 0.28 to 0.56/sec for $A = 350\ cm^2$ in the OGO instrument, and for $\rho = 10^{-9}$ cc. in a typical gaseous comet.

3.1.2 Electron-Ion Trap

The minimum detectable charged-particle density for an instrument of 10^{-13} amp/volt sensitivity is

$$N = (de/dt)/A\ v_h = 6.25 \times 10^5/A\ v_h. \tag{2-8}$$

For a detector area of 1 cm^2 moving at a relative velocity of 8 to 16 km/sec, the charge density ranges from 0.78 to 0.39/sec.

3.1.3 Ion Mass Spectrometer

Under the assumption that the relative spectrometer-ion velocity is the same as the relative spacecraft-comet velocity of 8 to 16 km/sec, an OGO-type flight ion-mass spectrometer with a 10^{-14} amp/volt sensitivity and a window area of 12 cm^2 will detect ion densities of 6.25×10^{-3} to 3.25×10^{-3} per cc. These minimum densities are compatible with comet ion densities. For example, the density of CO^+ ions in Encke at 10^4 km from the nucleus is at least 1/cc.

3.1.4 Neutral Mass Spectrometer

Generally speaking, a neutral mass spectrometer could be expected to detect neutral molecules only if the densities were 10^4 to 10^6 per cc. The densities of CN and C_2 molecules in the vicinity of the nucleus of Brooks (2) fall within this range.

3.1.5 Other Instruments

In addition to the particle-and-field instruments tabulated in Tables 3-1A and 3-1B, others are described in Appendix A.1.

3.2 OBSERVATIONS OF NUCLEUS

A set of five experiments directed toward the nucleus is listed in Table 3-2A along with the characteristics of instruments similar to those required to perform the observations. The instruments are the following:

a. Slow-scan television
[JPL, 1964; JPL, 1963 c]

b. Infrared photomultiplier radiometer
[JPL, 1964]

c. Infrared spectrometer
[JPL, 1964]

Table 3-1A Instrument Characteristics - Coma

INSTRUMENT / PARAMETERS	COMA PARTICLE-AND-FIELD MEASUREMENTS							
	TRIAXIAL HELIUM MAGNETOMETER	PIEZOELECTRIC MICROPHONE DUST DETECTOR	ELECTROSTATIC ANALYZER PLASMA PROBE	ION MASS SPECTROMETER	PLANAR-TRAP ELECTRON DETECTOR	INTEGRATING IONIZATION CHAMBER	TRAPPED-RADIATION GM COUNTER	BISTATIC RADAR RECEIVER
EXPERIMENTAL TECHNIQUE	Direct measurement of intensity and direction of magnetic field	Direct measurement of momentum and energy of dust	Direct measurement of energy spectrum and direction of solar wind	Direct measurement of relative abundances of ions	Direct measurement of flux and energy of electrons	Direct measurement of energy spectrum of cosmic rays	Direct measurement of spectra and distribution of magnetically trapped particles	Indirect measurement of electron density and variations
DEVELOPMENT STATUS	Flight units Mariner '64	Flight units Mariner '64	Flight units Mariner '64	Flight units OGO	Flight unit OGO	Flight units Mariner '64	Flight units Mariner '64	Breadboard stage
DIMENSIONS	El: 6 x 6 x 2" S: 4.5" sphere		S: 7 x 7 x 4" El: 6 x 6 x 4.5"	1 cu. ft.		6" sphere	82.5 in.^{3}	4" x 4" x 12"
WEIGHT	El: 4.8 lbs. S: 1.3 lbs	1.15 lbs	7.0 lbs	8 lbs	8 lbs	1.3 lbs	0.5 lb	10 lbs
POWER	7.0 w*	0.108 w	3.5 w peak	8 w	2 w	0.25 w	0.09 w	5 w
DYNAMIC RANGE	±360 γ	10^{-13} - 10^{-9} gm	40 - 9500 ev	1 - 45 amu	0 - 10 ev	10^{-3} - 10^{3}/sec	10^{-1}-5×10^{4}/sec	
SENSITIVITY	Noise: 0.1 γ rms Freq: 0 - 1 c/s	10^{-6} dyne-sec	10^{-13} amp 10^{8} p/cm^2-sec	10^{-14} amp/v	10^{-13} amp/v	p: E > 10 Mev e: E > 0.5 Mev	p: 0.5 - 8 Mev e: 40 - 70 kev	
FIELD OF VIEW	Along orthogonal axes	180 deg	48 deg			Omni	60 deg	Dipole Antenna pattern
RESOLUTION	Null: ±0.5 γ**		Angle: ±10 deg Energy: ±1%	1 - 6:0.5 amu 7 - 45:1 amu				
OUTPUT DATA	Pulse width	Digital	Pulse width	Pulse width	Pulse width	Digital	Digital	Digital
BITS/SAMPLE		(8 bits/frame)			45			

* from a 2400 c/s, 50 v rms square wave (true of all instruments)

** null stability over temperature operating range; linearity: ±0.1%.

El - electronics and power supply

S - sensor

N - noise

Table 3-1B Instrument Characteristics - Coma

PARAMETERS \ INSTRUMENT	COMA PARTICLE-AND-FIELD MEASUREMENTS							
	TRIAXIAL HELIUM MAGNETOMETER	PIEZOELECTRIC MICROPHONE DUST DETECTOR	ELECTROSTATIC ANALYZER PLASMA PROBE	ION MASS SPECTROMETER	PLANAR - TRAP ELECTRON DETECTOR	INTEGRATING IONIZATION CHAMBER	TRAPPED-RADIATION GM COUNTER	BISTATIC RADAR RECEIVER
ORIENTATION	Along S/C x, y, z axes	a. Normal to ecliptic b. Along S/C velocity vector	0 - 10 deg from probe-sun line	Along S/C velocity vector	Along S/C velocity vector	Omni field-of-view		Pattern peak toward Earth
STABILIZATION	±0.5 deg	±1 deg	±0.5 deg	±0.5 deg	±0.5 deg	---	±0.5 deg	±10 deg
NUMBER OF SENSORS	1	2	1 (3 sections)	1	1	2	4	1 receiver 2 dipoles
PREFERRED LOCATION	Away from equipment bay (El in bus)	Above equipment bay	On top of instrument bay			Away from max. mass concentration;	On top of instrument bay	Rx: Equipment bay Ant: Min. shadow
TOTAL WEIGHT	6.1 lbs	2.3 lbs	7.0 lbs	8 lbs	8 lbs	2.5 lbs	2.1 lbs	10 lbs
TOTAL POWER	7.0 w	0.215 w	3.5 w	8 w	2 w	0.5 w	0.36 w	5 w
SAMPLING RATE	a. 1/2.5 sec b. 1/10 sec							
TOTAL BIT RATE	a. 33 1/3 bps b. 8 1/3 bps	5 bps		150 bps				1.2 bps
THERMAL LIMITS	El: -20 to 65°C S: -55 to 55°C	-40° to +72°C	-10° to +80°C			-30° to + 70°C	-10° to 50°C	-40° to +100°C
MEASUREMENT TIME	0.04 sec for 3 axes	20.16 sec per cycle	7.56 or 30.24 min/cycle					

El - electronics
S - sensor

d. Ultraviolet spectrometer
[JPL, 1964]

e. Ultraviolet photometers
[JPL, 1964; JPL, 1963 c]

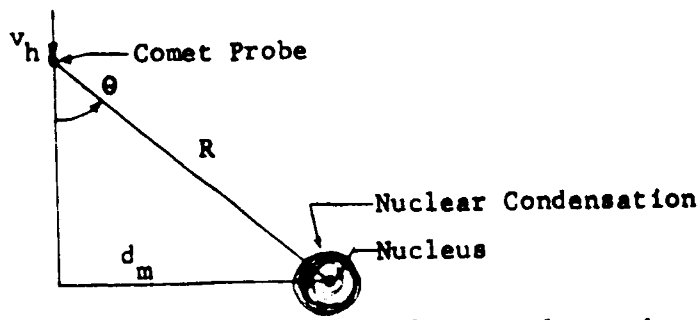
The requirements imposed upon subsystems by these instruments are tabulated in Table 3-2B.

3.2.1 Slow-Scan Television

The feasibility of using television subsystem with the performance of the Advanced Mariner TV has been established on the basis of the comet brightness model during a close approach to Pons-Winnecke's nuclear condensation. The Mariner-C television appears to have insufficient sensitivity (see Section 7.2 in Volume 6). The characteristics of the Advanced Mariner TV are tabulated in Table 3-2A. It is recommended that pictures be taken through yellow-red and blue filters when directed toward the nuclear condensation. The TV is located with photometers and a spectrometer on a tracking platform.

3.2.2 Comet Tracking Platform

The comet tracking platform is slaved to the comet tracker, which it supports. Figure 3-1 shows the variation of the maximum angular tracking rate as a function of expected miss distances and closing velocities, based on the planar geometry illustrated below.



The relation of angular tracking rate, tracking angle, and probe-nucleus

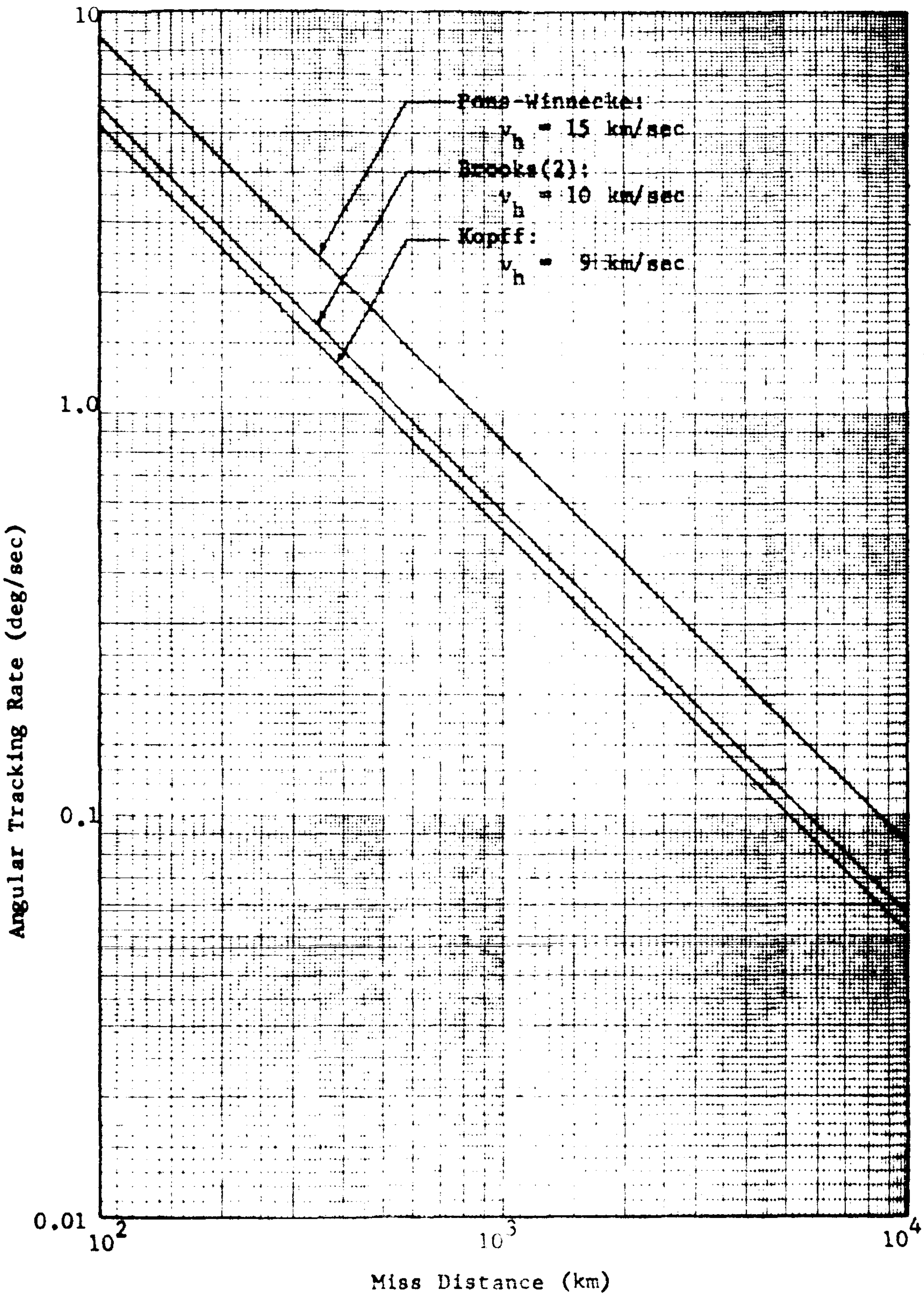


Fig. 3-1 Maximum Angular Rates for Tracking Platform Science

Table 3-2A Instrument Characteristics - Nucleus

PARAMETERS \ INSTRUMENT	NUCLEUS OBSERVATIONS: SLOW-SCAN TELEVISION	INFRA-RED SPECTROMETER	ULTRA-VIOLET SPECTROMETER	ULTRA-VIOLET PHOTOMETER
EXPERIMENTAL TECHNIQUE	Direct view of surface & its optical features	Measurement of IR fluorescence spectra	Measurement of comet UV fluorescence spectra	Measurement of UV comet intensity, scattered Lyman-α
DEVELOPMENT STATUS	Breadboard Adv. Mariner	Flight unit to be built	Prototype Mariner B	Flight unit Mariner '64
DIMENSIONS	20" x 10" dia.	12" dia x 15"	Op: 9"x10"x20" El: 6"x10"x6"	3" dia x 5"
WEIGHT	35 lbs	Op: 17.5 lbs* El: 7 lbs	22 lbs	1.5 lbs
POWER	16 w	4 w	12 w	1.5 w
DYNAMIC RANGE	100:1 illumination			10^3 - 10^8 Rayleighs
SENSITIVITY				Dark Current: 10^{-10} amp
FIELD OF VIEW	1.51°, 7.2°			Op: 2.5 deg.
RESOLUTION	1 km at 10,000 km	0.06μ		
OUTPUT DATA	Digital, pulse width			Pulse width
BITS/SAMPLE		5000	5000	

* Includes cooling of IR Detector
Op - optics
El - electronics
S - sensor

Table 3-2B Instrument Characteristics - Nucleus

INSTRUMENT / PARAMETERS	NUCLEUS OBSERVATIONS			
	SLOW-SCAN TELEVISION	INFRA-RED SPECTROMETER	ULTRA-VIOLET SPECTROMETER	ULTRA-VIOLET PHOTOMETER
ORIENTATION	Along probe-nucleus line	Along probe-nucleus line	Along probe-nucleus line	Along probe-nucleus line
STABILIZATION				
NUMBER OF SENSORS	1	1	1	4
PREFERRED LOCATION	Scan platform	Scan platform; shaded from sun	Scan platform	Scan platform
TOTAL WEIGHT	35 lbs	24.5 lbs	22 lbs	6.0 lbs
TOTAL POWER	16 w	4 w	12 w	6.0 w peak
SAMPLING RATE				(21 frame)
TOTAL BIT RATE				16 bps
THERMAL LIMITS	$0^{\circ}C$	-120° to $0^{\circ}C$		-20° to $+5^{\circ}C$
MEASUREMENT TIME		60 sec/scan		

distance for a given approach relative velocity v_h, and closest approach distance d_m (aiming point) is simply,

$$d\theta/dt = -(v_h \sin^2 \theta)/d_m. \tag{3-2}$$

3.2.3 IR Radiometer

A measurement of the surface temperature of the nucleus is desirable. However, estimated temperatures range from 100 to 200°K, so that the performance, physical characteristics, and requirements of the radiometer in Tables 3-4A and 3-4B may be incompatible with the high sensitivity demanded by such low temperatures.

3.2.4 IR and UV Spectrometers

The spectral regions selected for the scanning operation of the IR and UV spectrometers are those corresponding to the spectral emissions tabulated in Table 2-2, in particular for the CN, C_2, C_3 and CH molecules which occur in some abundance and have been observed from the earth in the periodic comets. Sensitive spectrometers are needed to establish the existence of OH, NH, NH_2 and O_I molecules in the coma heretofore not observed in the selected comets. In the coma and near the nucleus, ambiguous observations of the CH^+ and OH^+ ions have been recorded and could be confirmed.

3.2.5 UV Photometers

In addition to measuring the intensity of discrete wavelength emissions from known molecular components, UV photometers are to be used for measuring the intensity of solar Lyman-Alpha radiation scattered off molecular hydrogen in the coma and in the vicinity of the nucleus. Changes in scattered radiation are to be correlated with direct Lyman-Alpha radiation detected with a photometer aimed at the sun.

3.2.6 Other Instruments

In addition to the instruments for observing the nucleus tabulated in Tables 3-2A and 3-2B, others are described in Appendix A.2.

3.3 CHEMICAL COMPOSITION

The photometric and spectroscopic measurements discussed in Section 3.2 with regard to the nucleus apply also to determining the composition of the coma approached and traversed by the spacecraft. Moreover, the ion mass spectrometer considered in Section 3.1 with regard to particle-and-field measurements applies.

The chemical analysis of cometary material by such techniques as gas chromatography, alpha-particle scattering and neutron activation [JPL, 1963 b] depends upon collecting adequate samples from the rarefied atmosphere of the coma at high relative particle velocities. These techniques appear feasible only on a mission in which the spacecraft paces the comet in the vicinity of the nucleus or actually lands on the nucleus to extract samples.

3.4 REPRESENTATIVE PAYLOAD

Table 3-3 represents a full complement of scientific instruments for determining the distribution of matter and of the magnetic field through the coma of selected comets (P), for observing the nucleus (O), and for determining the chemical composition of cometary material (C).

3.4.1 Mariner-C Comparison

Referring to Table 3-3, items 1, 2, 3, 5, 6 and one each of items 8 and 9 are identical to the Mariner-C science complement. It is shown

Table 3-3. REPRESENTATIVE COMET PROBE SCIENCE PAYLOAD (ATLAS-CENTAUR)

	Instrument	Weight (lb)	Power (w)	Function
1.	Magnetometer	6.1	7.0	P
2.	Dust Detectors (2)	2.3	0.2	P
3.	Plasma Probe	7.0	3.5	P
4.	Ion-Electron Trap	8.0	2.0	P
5.	Ionization Chamber	2.6	0.5	P
6.	GM Tube	2.1	0.4	P
7.	Ion-Mass Spectrometer	8.0	8.0	P,C
8.	Lyman-Alpha Photometers (2)	3.0	3.0	P,C,O
9.	UV Photometers (2)	3.0	3.0	C,O
10.	UV Spectrometer	22.0	12.0	C,O
11.	Television	35.0	16.0	O
	Totals	99.1 lbs	55.6	

Note: Bit rates, thermal limits, orientation and preferred S/C location of each instrument are given in Tables 3-1B and 3-2B.

in Section 5 of Volume 9 that a Mariner-C launched with an Atlas-Agena in 1969 can be modified to include an ion-mass spectrometer (item 7) and a gimbaled comet tracker to direct two UV photometers toward the nucleus (item 9) in addition to supporting two Lyman-alpha photometers (item 8). It is also shown that a modified Mariner-C launched with an Atlas-Agena in 1970 can support, in addition, an Advanced Mariner television subsystem (item 11) to observe the nucleus.

Table 3-4 compares the science payloads of the basic Mariner and its near-minimal and maximal modifications.

Table 3-4. Mariner-C Comet Probe
Science

Instrument	Mariner-C (1964)	Mariner Mod. 1969	Mariner Mod. 1970
Magnetometer	x	x	x
Dust Detectors (2)	x	x	x
Plasma Probe	x	x	x
Ionization Chamber	x	x	x
GM Tube	x	x	x
Ion-Mass Spectrometer		x	x
Lyman-Alpha Photometer	x	x (2)	x (2)
UV Photometer	x	x (2)	x (2)
Television	x		x
UV Spectrometer*			(x)
Ion-Electron Trap*			(x)

* Alternative couple to the television.

SECTION 4
ASTEROID MODEL AND EXPERIMENTS

4.1 PHYSICAL PROPERTIES

The orbital characteristics of five close-approach asteroids are tabulated below in Table 4-1.

Table 4-1 Orbital Characteristics of Close-Approach Asteroids

ASTEROID	Period (yr)	q (A.U.)	a (A.U.)	e	i (deg)	Closest Earth Dist. (A.U./yr)
Icarus	1.12	0.186	1.078	0.827	23.0	0.042 / 1968
Geographus	1.388	0.827	1.244	0.335	13.325	0.073 / 1969
Hermes	1.466	0.677	1.290	0.475	4.685	0.005 / 1937
Eros	1.761	1.133	1.458	0.240	10.831	0.150 / 1975
Apollo	1.812	0.645	1.486	0.566	6.422	0.070 / 1932

Significant data on their physical properties are scarce because all are fast-moving small objects that have allowed only short observation times. A digest of the physical properties and composition of close-approach asteroids in given below:

Shape	:	Irregular (Eros	:	22 x 6 km)
Size	:	Icarus	:	1.4 km
		Geographus	:	2.0 km
		Eros	:	22.0 km
Apparent Magnitude	:	Icarus	:	18
		Eros	:	9 to 10.4
Rotation Period	:	Eros	:	5.5 hr
Density, Mass	:	Unknown		
Surface Temperature	:	Icarus	:	800°K
Composition	:	Alumino-silicates, silicates, nickel-ferrous compounds		
Atmosphere	:	No atmosphere indicated		
Magnetic Field	:	Unknown		

4.2 POSSIBLE EXPERIMENTS

The following experiments in the vicinity of a close-approach asteroid are suggested:

EXPERIMENT	OBJECTIVE	TECHNICUE
Visual Observation	Ascertain shape, size and rotation	TV with color filters (e.g., Mariner '64)
Infrared Radiometry	Determine surface temperature	IR Radiometer (e.g., Mariner 2)
Ultraviolet Photometry	Determine surface emissions	UV Photometer (e.g., Mariner '64)
Magnetic Field	Measure direction and intensity	Magnetometer (e.g., Mariner '64)
Mass	Determine mass and density	S/C trajectory deflection-Radar ranging system

4.2.1 Particles and Fields

The detection of a magnetic field near an asteroid is a link in the determination of the origin of the asteroids and their composition. Thus careful measurements of the change in the interplanetary magnetic field in the vicinity of an asteroid should be conducted. Simultaneous observations of the solar wind with a plasma probe are desirable.

The equilibrium temperatures of a rotating body like Eros with no internal heating should be close to $300^{\circ}K$. An IR radiometer or microwave radiometer will accomplish the measurement.

4.2.2 Electro-Optical Observations

Photometric, spectroscopic and television observations from the solar side of the illuminated asteroidal surface will yield measurements of the spectral intensity of scattered sunlight, and an indication of its shape and of its grosser surface features. A miss distance of 1000 km from Eros, a 22 km x 6 km body, is compatible with the resolution achieved with Mariner-C television optics i.e., 1 km at 10,000 km. Visual observations require a very small miss distance of a few hundred kilometers or less to ascertain surface features. The measurement of spacecraft trajectory deflection and the feasibility of radar ranging are also improved by a close miss.

4.2.3 Chemical Composition

Chemical analysis techniques can be performed only from the asteroid surface and thus require a lander mission. Spectroscopic measurements, however, can provide data from which the surface composition can be estimated.

SECTION 5
CONCLUSIONS

5.1 COMET AND CLOSE-APPROACH ASTEROID MISSIONS

The report analyzes what is known about the geometry, brightness and composition of comets to the extent necessary for conducting a mission analysis and for designing conceptual spacecraft. Such comet "models" have been developed to specify requirements of scientific instruments for performing comet measurements, to assess the applicability of existing instrumentation, and to determine the influence of the comet environment upon subsystem design and mission capability. Astrophysical and exobiological scientific objectives have been identified and representative comet payloads established to determine the distribution of matter and magnetic field during a fly-through, to observe the nucleus and its surrounding region, and to determine cometary chemical composition.

Scientific measurements performed from on-board a spacecraft during its intercept with a comet fulfill two roles in determining the composition of comets. The first function is to complement measurements performed from earth astronomical observatories by <u>direct</u> sampling of the particle, field and molecular composition of a comet, by close-range observation of its physical features, and by detecting predicted but unobserved spectral emissions. The second function is to supplement measurements performed on the earth by confirming spectral lines previously recorded, especially those that are ambiguously identified. On-board measurements can better serve their complementary and supplementary functions if they are correlated with simultaneous photometric and spectroscopic observations from Earth.

The compatibility of particle-and-field experiments for comet intercepts with basic interplanetary measurements is unique to this type of encounter mission.

The scientific feasibility of comet missions with an Atlas-Centaur launch vehicle during 1967-1975 has been established.

A mission to the close-approach asteroid Eros is outlined to establish growth potential for the comet probe.

The scientific feasibility of a comet missions to Pons-Winnecke with an Atlas-Agena/Mariner-C during late 1969 and early 1970 has been established.

SECTION 6

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APPENDIX A
INSTRUMENT SUPPLEMENT

A.1 PARTICLE-AND-FIELD INSTRUMENTS

Data sheets on the following instruments are presented in this section to supplement the instruments tabulated in Tables 3-1A to 3-1B for performing particle and field measurements in Cometary Coma:

1. OGO-C Massenfilter
   [Leite, 1964]
2. JPL Ion Mass Spectrometer
   [Giffin, 1964]

In addition, a brief summary of an infra-red and visible-light photometric dust detector [Cooley, 1964] is presented.

A.1.1 University of Michigan OGO-C Massenfilter

The following parameters describe the overall characteristics of the OGO Massenfilter:

Dimensions	8 x 8 x 8 in.
Weight	8.3 lbs.
Power	36 wattspeak; 23.8 watts average
Dynamic Range	0-50 AMU (spectra) 0-40 AMU (integrated mass flow)
Sensitivity	10^{-10} to 10^{-15} amp per volt
Window Area	5.5 degree conical look angle
Resolution	2 AMU at 40 AMU; $M/\Delta M = 20$ at half-amplitude
Output Data	Analog (0-5 volts)

Thermal Limits	$0^{o}C$ to $40^{o}C$ (operational)
Measurement Time	5 sec. (sweep over spectrum) 30 sec. (complete ion mode survey) 30 sec. (complete neutral mode survey) 70 sec. (complete cycle of operation)

A.1.2 JPL Ion Mass Spectrometer

Dimensions	12 x 6 x 3 inches
Weight	10 lbs.
Power	10 w
Dynamic Range	1 - 66 AMU
Sensitivity	3 atoms/cc
Field of View	60-degree cone
Resolution	M/ M > 40
Output Data	Digital
Bits	3000 bits/sepctrum for 1% peak measurement
Measurement Time	Data accumulated in 50 to 60 sec of continuous scanning during approach at 3 km/sec relative velocity; instrument designed for lunar atmosphere measurements

A.1.3 IR-Visible Photometric Dust Detector

Exotech, Inc. has conducted experimental programs that show that high-velocity punctures can be detected with infra-red sensors that observe the radiation produced in a vacuum from impact and puncture of a thin target. Experiments show a correlation between the intensity of the infra-red signal and the projectile's kinetic energy; so that, if the impact velocity is measured, the particle mass can be calculated.

Analysis of data by North American Aviation on the effective color temperature of impact flash at the time of peak luminosity for 50-micron Pyrex spheres on aluminum shows that the effective temperature varies approximately as the 0.35 power of velocity from 6 to 14 km/sec. (Relative spacecraft-comet velocities range from 8-16 km/sec). By assuming a black-body spectral distribution and calculating the peak black-body radiation corresponding to the North American Aviation measurements in the visible spectrum, a dependence of the peak black-body radiance on the 3.2 power of velocity was found, which is in approximate agreement with the velocity-cubed dependence determined from infrared impact-flash measurements made during this program and which is predicted on the basis of a dimensional analysis of the impact flash process.

Further research is desirable to determine more precisely the spectral distribution of impact-flash, puncture-flash and back-spatter flash signals as a function of time after impact for the range of projectile and target parameters which are of potential utility for advanced meteoroid instrumentation systems.

Two lead-sulfide (PbS) IR-sensor units have been developed by Exotech and tested at pressures down to 1.1×10^{-8} Torr for operation in the 0.7 to 2.5-micron wavelength region.

A.2 OBSERVATIONS OF NUCLEUS

Data on the following instruments are presented to supplement the instruments tabulated in Tables 3-2A and 3-2B for performing photometric and spectroscopic measurements on the nucleus and in the coma:

(1) NRL Lyman-alpha photometer
[Randall, 1964; Randall, Hanley and Larison, 1963]

Most of the NRL rocket-flight spectrometers operate below 2000Å and thus outside the region of cometary interest [Siomkajlo, 1964].

(2) Cook Electric Company scanning spectrometer [Cook, 1964]

A.2.1 NRL Lyman-Alpha Photometer

Dimensions-Detector	3.4 cm dia x 2.4 cm long
Weight	33.3 grams
Spectral Range	1040-1340Å
Resolution	10Å
Sensitivity	40% Efficiency
Exposed Detector Area	about 3/8" diameter
Angular Field of View	± 40 deg.
Thermal Limits During Operation	-15°C to +15°C
Flight History	a) Aircraft b) Rocket

A.2.2 Cook OAO-A Scanning Spectrometer

Dimensions	15 x 9½ x 45¼ inches
Weight	52 lbs
Spectral Range*	1000 - 4000 Å in two overlapping bands
Resolution	Selectable slit widths: 10 and 100Å 20 and 200Å
Output Data	Digital and analog
Thermal Limits	-55°C to +72°C

* Useful range for cometary spectral emissions is 3000 - 4000Å